

High-Energy Activity in the Unusually Soft TeV Source HESS J1804-216 toward the Galactic Center

Marco Fatuzzo¹, Fulvio Melia², and Roland M. Crocker³

¹*Physics Department, Xavier University, Cincinnati, OH 45207*

²*Physics Department and Steward Observatory, The University of Arizona, AZ 85721*

³*School of Chemistry and Physics, The University of Adelaide, South Australia 5005*

ABSTRACT

In recent years, apparent anisotropies in the EeV cosmic ray (CR) flux arriving at Earth from the general direction of the galactic center have been reported from the analysis of AGASA and SUGAR data. The more recently commissioned Auger Observatory has not confirmed these results. HESS has now detected an unusually soft TeV source roughly coincident with the location of the previously claimed CR anisotropy. In this paper, we develop a model for the TeV emission from this object, consistent with observations at other wavelengths, and examine the circumstances under which it might have contributed to the \sim EeV cosmic ray spectrum. We find that the supernova remnant G8.7-0.1 can plausibly account for all the known radiative characteristics of HESS J1804-216, but that it can accelerate cosmic rays only up to an energy $\sim 10^5$ GeV. On the other hand, the pulsar (PSR J1803-2137) embedded within this remnant can in principle inject EeV protons into the surrounding medium, but it cannot account for the broadband spectrum of HESS J1804-216. We therefore conclude that although G8.7-0.1 is probably the source of TeV photons originating from this direction, there is no compelling theoretical motivation for expecting a cosmic ray anisotropy at this location. However, if G8.7-0.1 is indeed correctly identified with HESS J1804-216, it should also produce a \sim GeV flux detectable in a one-year all sky survey by GLAST.

Subject headings: acceleration of particles—cosmic rays—Galaxy: center—galaxies: nuclei—radiation mechanisms: nonthermal—supernova remnants

1. Introduction

The High Energy Stereoscopic System (HESS) array provides sensitivity to gamma rays with energy > 100 GeV at a level below 1% of the flux from the Crab Nebula, with

an angular resolution for individual photons better than 0.1° . Thus, the position of even relatively faint sources may be determined with an error of only 30 sec. A scan of the inner 60° of the galactic plane has identified fourteen discrete TeV-emitting sources, half of which have plausible identifications at other wavelengths (Aharonian et al. 2005). HESS J1804-216 is the source at galactic coordinates $l = 8.40^\circ$ and $b = -0.033^\circ$, with a TeV-size of ≈ 22 arcmin. Its estimated flux above 200 GeV is $5.3 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$, with a statistical error of 10 to 35%. Its spectral (power-law) index is -2.72 ± 0.06 , the steepest of all the TeV sources in this survey (Aharonian et al. 2006).

This source coincides with the southwestern rim of the shell-type SNR G8.7-0.1 (W30), whose radio-emitting radius has been set at ≈ 26 arcmin (see, e.g., Handa et al. 1988). Its radio flux at 1 GHz may be derived from the Green (2004) catalog, assuming a radio spectral index $\alpha \sim -0.65$, and integrating from 10^7 to 10^{11} Hz (Helfand et al. 2005). Such an estimate yields a radio flux for G8.7-0.1 of $1.1 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$.

From CO observations, it is known that the W30 complex is surrounded by molecular gas (Blitz, Fich, & Stark 1982), in which new stars are forming. By associating G8.7-0.1 with coincident H II regions whose distances are known, Kassim & Weiler (1990) have estimated a distance to the SNR of 6 ± 1 kpc which, combined with its angular size of ~ 50 arcmin, implies a physical size of ~ 80 pc. Thus, if HESS J1804-216 is indeed associated with this SNR, its location is not quite at the galactic center (i.e., at a distance of ≈ 8.5 kpc).

G8.7-0.1 may also be linked with the (relatively) young pulsar PSR J1803-2137, an association suggested by their coincidence on the sky, and by the observed dispersion measure, which points to a distance of ~ 5.3 kpc (Clifton & Lyne 1986). Both sources were observed with the Position Sensitive Proportional Counter at the focus of ROSAT (Finley & Ögelman 1994), and both were detected in the soft X-ray energy band $0.1 - 2.4$ keV. For G8.7-0.1, the unabsorbed flux in this range of wavelengths is estimated to be $\sim (1 - 3) \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1}$, corresponding to a luminosity $(0.4 - 1.3) \times 10^{36} \text{ ergs s}^{-1}$ (for a distance of 6 kpc). On the other hand, there is no known detection of either source at \sim GeV energies, implying an upper limit to their EGRET (i.e., 100 MeV to ~ 30 GeV) flux of $\sim 4 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$ (Hartman et al. 1999).

Several of these new TeV sources have raised important questions concerning their origin. HESS J1804-216, in particular, is characterized by an unusually steep gamma ray spectrum, yet it was not detected by EGRET in the GeV range, as one might naively expect based on an extrapolation of the HESS data to lower energies. Clearly, the spectrum cannot be a simple power law, and must display some interesting physics between GeV and TeV energies, possibly shedding some light on the connection between particle acceleration, diffusion, and emissivity. Addressing these questions is one of the principal goals of this paper.

But interest in the high-energy activity in this region of the Galaxy extends beyond just these issues (see, e.g., Melia and Falcke 2001). The analysis, in recent years, of data from two different cosmic ray detectors has suggested the presence of an anisotropic overabundance of cosmic rays coming from the general direction of the galactic center at energies around an EeV (10^{18} eV). Statistically, the most robust determination for an anisotropy has been made by the Akeno Giant Shower Array (AGASA) Group (Hayashida et al. 1999), which found a strong—4% amplitude—anisotropy in the energy range $10^{17.9} - 10^{18.3}$ eV. Two-dimensional analysis of the data showed that this anisotropy could be interpreted as an excess of air showers from two regions each of $\sim 20^\circ$ extent, one of 4σ significance near the galactic center and another of 3σ in Cygnus. Interestingly, AGASA also saw a CR deficit towards the Galactic anti-center.

Prompted by this result, Bellido et al. (2001) re-analyzed the data collected by the SUGAR cosmic ray detector, which operated near Sydney from 1968 to 1979. They confirmed the existence of an anisotropy, consistent with a point source located 7.5° from the galactic center—and 6° degrees from the AGASA maximum over an energy range of $10^{17.9} - 10^{18.5}$ eV.

Not surprisingly, this tentative result has generated some intense theoretical interest because although it has long been speculated that diffusive shock acceleration of protons and ions at shock fronts associated with supernova remnants (SNRs) is the mechanism likely responsible for energizing the bulk of high energy cosmic rays, the observational evidence for this has been elusive. In addition, the conditions at almost all known SNRs seem not to promote the acceleration of CRs beyond the ‘knee’ feature in the spectrum, at $\simeq 5 \times 10^{15}$ eV. Thus, the origin of CRs between the knee and the ‘ankle’ at $\text{few} \times 10^{19}$ eV has been a mystery.

In a series of earlier papers (Crocker et al. 2005a, 2005b; see also Bossa et al. 2003, Aharonian and Neronov 2005, and the original discussion in Markoff et al. 1997, 1999), we explored in detail the physics of particle acceleration and radiative emission in the central few parsecs of the Galaxy to examine the extent to which detectors on Earth would be able to sense neutrinos originating at the galactic center, and to understand how a cosmic ray anisotropy might fit into the overall astroparticle scheme associated with this dynamic region of the Galaxy.

But there are several serious difficulties that a comprehensive and self-consistent model of the energetic particle activity at the galactic center must overcome (Melia & Falcke 2001; Melia 2006). For example, not all of the data can be accommodated within a solitary framework, at least not one focusing on the nucleus itself; indeed, the data are inconsistent amongst themselves in two important instances: (i) the SUGAR results indicate a point

source offset by 7.5° (toward positive galactic latitude) from the galactic center, in (at least partial) disagreement with AGASA, and (ii) the \sim TeV and (EGRET) γ -ray emissivities are not simple extensions of a single spectrum.

Even at \sim EeV energies, charged particles would not be able to reach Earth directly without being significantly deflected by the intervening magnetic field. A consensus has developed that, if real, this CR anisotropy would be caused by neutron emission at the galactic center, an idea first mooted by Jones (1990). The anisotropy ‘turn on’ at a definite energy of \sim EeV finds a natural explanation in the fact that this energy corresponds to a Lorentz factor for neutrons large enough that they can reach us from the center of the Milky Way. Neutrons below this energy decay in transit and are then diverted by galactic magnetic fields. Above $\sim 10^{18.4}$ eV, the anisotropy ceases due to either a very steep galactic center source spectrum or an actual cut-off in the source so that the background takes over again at this energy.

Note, moreover, that the galactic center, with declination $\delta = -28.9^\circ$, is outside the field of view of AGASA (which is limited to $\delta > -24^\circ$; Bossa et al. 2003), but not so for SUGAR. Thus, the discrepancy between the two source positionings may simply be due to the fact that AGASA is seeing protons produced during in-flight neutron decay, whereas SUGAR sees the neutron source directly. That the SUGAR anisotropy is not coincident with the galactic center, however, still presents a challenge to all scenarios that would posit an EeV source right at the nucleus. Either, all such models are incorrect or the SUGAR directional determination is somewhat in error. If not the galactic center, then the SUGAR anisotropy could be due to another source displaced from the galactic center by approximately 8° toward positive galactic latitude.

Another serious problem with the data sets is that whereas the galactic center is outside the field of view of AGASA, the position of the SUGAR maximum is inside the AGASA field of view so that the putative SUGAR source should be seen by AGASA. Of course, one way out of this dilemma is that the source may have varied between the SUGAR and AGASA observation times; this might occur, for example, if the source of energetic particles were a pulsar.

One cannot ignore the fact that the new TeV source, HESS J1804-216, coincides with the previously cataloged SNR, G8.7-0.1, at about the position where SUGAR detected the source of CR anisotropy. Could this be the smoking gun that finally provides the observational evidence of a link between EeV particle acceleration and a known source?

Unfortunately, such an evaluation is not quite straightforward. The Pierre Auger Observatory has now acquired enough data to search for an excess of events near the direction of

the galactic center in several energy bands around an EeV. With the accumulated statistics—1155 events, compared with an expected number of 1160.7 for the energy range $(1.0 - 2.5)$ EeV—already larger than that of any earlier experiment, including AGASA and SUGAR (the event number of AGASA in this region is only 1/3 of this), the Auger Observatory does not confirm the previously reported CR anisotropy (Letessier-Selvon et al. 2005). This raises several pertinent questions that we wish to address in this paper. (1) Though unlikely, could it be that Auger is wrong, and that the TeV characteristics of HESS J1804-216 would support the view that SUGAR (and possibly AGASA) are in fact correct? Finding a model of HESS J1804-216 as the source of TeV gamma rays, not violating observed flux limits at other wavelengths, and producing \sim EeV particles, could lend important support to this viewpoint. (2) On the other hand, if Auger is correct, and no CR anisotropy is evident from the galactic center, then what is the nature of HESS J1804-216, and can one account for it using more ‘conventional’ means, i.e., by identifying it as a member of a known class of object? (3) Finally, how likely is it that HESS J1804-216 may have produced variable EeV emission over the past ~ 30 years? In the next section, we shall develop viable models of its high-energy activity, and then discuss its role in a broader context in § 3.

2. Two Possible Sources for the TeV Photons

2.1 The Pulsar PSR J1803-2137

Young, rapidly spinning pulsars have long been viewed as viable sources of cosmic rays, possibly capable of accelerating hadrons to energies greater than $\sim 10^{20}$ eV (Blasi et al. 2000; Arons 2003). We consider here the possibility that relativistic particles produced by PSR J1803-2137 lead to a pionic-decay photon emissivity, accounting for the HESS J1804-216 source. We also ascertain the likelihood that PSR J1803-2137 is the source of excess cosmic rays reported by SUGAR and AGASA.

Following Blasi et al. (2000) and Arons (2003), we consider the acceleration of charged particles across voltage drops in the relativistic winds near the light cylinder of young, rapidly rotating neutron stars. These particles do not suffer from the radiation losses that limit their polar cap or outer gap counterparts to energies $\sim 10^{16}$ eV (see, e.g., Arons 2003); as such, they can reach a maximum energy of

$$E_{\max}(\Omega_0) \approx \eta Z e \Phi_{\text{wind}} = \eta Z e \frac{\Omega_0^2 \mu}{c^2} = 3 \times 10^{18} Z \left(\frac{\eta}{0.1} \right) \left(\frac{\Omega_0}{10^4 \text{ s}^{-1}} \right)^2 \left(\frac{B_*}{10^{12} \text{ G}} \right) \text{ eV}, \quad (1)$$

where η is the fraction of the voltage drop, Φ_{wind} , experienced by the charges, B_* is the surface magnetic field strength (giving rise to a magnetic moment $\mu \equiv B_* R_*^3$, in terms of the stellar radius R_*) and Ω_0 is the initial pulsar rotation frequency. In the case of PSR J1803-2137, its measured spin-down age (Kassim and Weiler 1990) implies a magnetic field strength $B_* \approx 8.6 \times 10^{12}$ G, and therefore $E_{\max} \sim 24$ EeV.

As rotational energy is transferred to the particles, the pulsar spins down, and the injected particle energy drops. As a result, the particles accelerated over the pulsar's spin-down lifetime produce a power-law distribution

$$N(E) = \frac{9}{4} \frac{c^2 I}{Z e \mu} E^{-1}, \quad (2)$$

where I is the neutron star's moment of inertia. The fact that PSR J1803-2137 has a present day period of 133 ms, means that the distribution in this case extends down in energy only as far as $E_{\min} \approx 6 \times 10^5$ GeV, estimated from Equation (1) by setting Ω_0 to its current value.

The interaction of the accelerated, power-law (i.e., $N(E) = N_0 E^{-1}$) particles, assumed here to be protons, with an ambient medium of density n_p , leads to the production of pions and, subsequently, photons from the decay of neutral pions and secondary lepton emission. Since Equation (2) directly yields the number of relativistic protons injected into the surrounding medium once the magnetic field strength is specified, the cascade-induced emissivity depends solely on the properties of the ambient medium, e.g., its number density.

(A full description of the pp induced particle cascade and resulting broadband radiative emissivity is provided in Fatuzzo & Melia [2003; hereafter FM03] and Crocker et al. [2005a], and will therefore not be reproduced in detail here.¹) However, the rate at which these cosmic rays diffuse out of the scattering region depends on their rigidity and therefore on their energy. As a result, the energy distribution of the particles remaining in the interaction zone will differ from the simple scaling implied by Equation (2) and, moreover, this distribution evolves in time as the diffusion process differentiates between particles of different energy.

But one does not need to analyze the diffusion process in great detail to see that PSR J1803-2137 could not be the source of TeV photons in HESS J1804-216. The reason is that $E_{min} \gg 1$ TeV, and regardless of how the energy-dependent diffusion modifies the cosmic ray distribution at the source, the photon spectrum below E_{min} would have an index ≈ -1 , at odds with the observed value -2.7 . One can see this in Figure 1, where we show the calculated photon spectrum in comparison with the TeV data, under the most favorable assumption that diffusion could somehow produce a proton distribution with index -2.7 . The photon emissivity below E_{min} is dominated by the π^0 cascade initiated by cosmic rays in the energy range $\sim 6 \times 10^5 - 6 \times 10^6$ GeV, and this is true for all proton power-law indices < 0 . It therefore appears that under all circumstances, the contribution of PSR J1803-2137 to the TeV photon spectrum is too flat to account for the HESS data.

Even so, PSR J1803-2137 could still account for the putative cosmic ray anisotropy at \sim EeV energies, without contributing measurably to the observed TeV flux, if the proton spectral index is ~ -1 (see Crocker et al. 2005a). It should be noted, however, that the production of neutrons within this scheme results from charge exchange in pp scattering. A present day neutron production associated with particles accelerated by PSR J1803-2137 would then require that the diffusion time for EeV protons (which would have been injected very early on by the pulsar) out of the surrounding region could not be much less than the pulsar age, and that the surrounding region have a density below 10 cm^{-3} so as to not violate the observed HESS data, as shown in Figure 1 (note that the photon emissivity scales directly with the ambient density).

2.2 The SNR G8.7-0.1

The expansion of an SNR into a dense molecular cloud can produce shock accelerated protons whose interactions with that medium (via pp scattering) may also lead to an observable pionic decay signal above ~ 100 MeV (Drury et al. 1994; Sturmer et al. 1997). Indeed,

¹It is worth pointing out, though, that FM03 use the empirical fits to the accelerator data based on a hybrid isobar/scaling model (Dermer 1986a,b). These fits are similar, but slightly different, from the cross sections used in other SNR treatments (see, e.g., Drury et al. 1994; Gaisser et al. 1998; Baring et al. 1999).

this mechanism has been invoked to account for the association of several EGRET sources with SNRs interacting with their dense surroundings (see, e.g., Gaisser et al. 1998; Baring et al. 1999; Berezhko & Völk 2000; Fatuzzo & Melia 2005).

In this section, we consider whether the broadband emission powered by SNR shocks in G8.7-0.1 can account for the HESS J1804-216 source without violating the flux limits observed at other wavelengths. We assume that shock acceleration within the SNR environment injects a power-law distribution of relativistic protons with a spectral index $\alpha = 2.0 - 2.4$ and maximum energy E_{max} into a dense (500 cm^{-3}) shell at the SNR-cloud boundary (e.g., Chevalier 1999; Fatuzzo & Melia 2005). The value of E_{max} can be approximated by taking the product of the remnant’s age with the energy-gain rate for particles in a shock,

$$\dot{E}(t) = 10^8 \frac{B v_8^2(t)}{f R_J} \text{ eV s}^{-1}, \quad (3)$$

where B ($\approx 10^{-5} \text{ G}$) is the magnetic field strength, v_8 is the shock velocity in units of 10^8 cm s^{-1} , $f \sim 10$ is the particle mean free path along the magnetic field in units of its gyroradius, and $R_J \sim 1$ is a factor that accounts for the orientation of the shock relative to the magnetic field (Sturmer et al. 1997). For the SNR age $T_{SNR} \sim 15,000$ years (Kassim and Weiler 1990), and canonical values of the parameters, we estimate $E_{max} \sim 10^5 \text{ GeV}$. Since this value exceeds the HESS date range for HESS J1804-216, we ignore any high-energy truncation in the proton distribution when calculating the pion-decay spectrum.

In order to calculate the pp-initiated cascade leading to the gamma ray emissivity, one must know the current relativistic proton distribution in the interaction region. Once these particles leave the shock acceleration region, they diffuse into the dense ($n \sim 500 \text{ cm}^{-3}$) molecular environment where they scatter with the low-energy ambient medium, though some eventually leave the system without scattering. Given the $\sim 40 \text{ mbarn}$ pp scattering cross section, we estimate the cooling time scale for these cosmic rays to be $\sim 70,000$ years, much longer than the age of the remnant. (In reality, the pp scattering cross section increases slowly with energy, such that this time scale shrinks to $\approx 15,000$ years for cosmic rays with energy $\approx 1.7 \text{ EeV}$. At this energy, however, the protons escape directly from the source.) As such, the injected proton distribution evolves primarily under the influence of energy-dependent diffusion, according to the simplified equation

$$\frac{dN(E)}{dt} = Q(E) - \frac{N(E)}{\tau(E)}, \quad (4)$$

where $Q(E)$ is the injection rate and

$$\tau \equiv \frac{R^2}{D(E)} \quad (5)$$

is the diffusion time scale, in terms of the system size R and the diffusion coefficient $D(E)$. To simplify the procedure, yet retain the essential physics, we solve this equation in two limits: (i) for energies such that $\tau(E) \gg T_{SNR}$, we put $N(E) = Q(E) T_{SNR}$; (ii) for energies such that $\tau(E) \ll T_{SNR}$, we take $N(E) = Q(E) \tau(E)$. The resulting power laws are connected smoothly at the energy E_{roll} where $T_{SNR} = \tau(E)$.

Unfortunately, the process of diffusion (here characterized by the diffusion coefficient $D(E)$) is not well understood, and several viable prescriptions exist. To quantify the dependence of our results on the range of possibilities, we will use the formulation

$$D(E) \equiv \left(\frac{\lambda_{max} c}{3\mu} \right) \left(\frac{E}{ZeB \lambda_{max}} \right)^{2-\beta}, \quad (6)$$

where λ_{max} is the scale size of the largest magnetic fluctuations in the system (often similar to the scale size of the dynamical disturbance), μ (~ 1) represents the magnitude of the magnetic fluctuations relative to the underlying global field, and β is the index characterizing the fluctuation spectrum for the various prescriptions of turbulence, i.e., $\beta = 1$ for Bohm diffusion, $3/2$ for Kraichnan diffusion, and $5/3$ in the case of Kolmogorov diffusion. In what follows, we shall examine the impact of all three forms of diffusion, and ascertain whether any may be ruled out for this system given the currently available data for HESS J1804-216.

The actual value of E_{roll} is rather sensitive to the choice of R and λ_{max} (and to a lesser extent, B). For reasonable choices ($R \sim 1 - 10$ pc and $\lambda_{max} \sim 1 - 10R$) of these variables, E_{roll} ranges over several decades and spans the whole HESS energy range. As such, E_{roll} effectively functions as a free parameter, since neither R nor λ_{max} are known precisely.

We show in Figures 2, 3, and 4 the gamma ray spectra of particle distributions injected into the medium by shocks in SNR G8.7-0.1, and subsequently modified in energy by diffusion. For all three cases of diffusion, the particle distribution index above E_{roll} is -2.7 , but in order to attain this value with the different β 's, the assumed proton injection power-law must be modified accordingly. A quick inspection of these three figures indicates that the principal impact of this feature is to alter the spectrum below E_{roll} , where the particles have not yet had time to diffuse through the medium. As such, the photon spectrum in this region is shaped by $Q(E)$. Thus, the spectrum below E_{roll} is hardest for Bohm diffusion (Figure 2), and it softens progressively from Bohm to Kraichnan (Figure 3), and then to Kolmogorov (Figure 4).

Under the assumption of a uniform and steady injection rate $Q(E)$, as we have adopted here, only the Bohm diffusion scenario results in a photon spectrum that does not violate the EGRET upper limit. Because the ensuing emissivity scales as the product $N \cdot n_p$, the energy content of the relativistic particles is given by $U_E \approx 10^{49} (n_p/500 \text{ cm}^{-3})^{-1}$ ergs,

which represents approximately 1% of the supernova energy for the assumed density. In this case (of Bohm diffusion), the integrated flux between 100 MeV and 30 GeV is found to be $6 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$, and thus falls right at the EGRET threshold. In the near future, GLAST will greatly improve the sensitivity of measurements in this energy range, and will therefore provide an important probe into the possible association of HESS J1804-216 with SNR G8.7-0.1. In fact, the ~ 1 GeV emission should be detectable with GLAST after a one-year all-sky survey (indicated by the thick solid lines in Figures 2, 3, and 4) regardless of which prescription of diffusion is active.

For completeness we calculate the broadband emissivity for the case of Bohm diffusion by including the flux contributions from secondary leptons (as outlined in detail in Fatuzzo & Melia 2003). The decay of charged pions leads to the production of electrons and positrons in the scattering environment that in turn radiate via bremsstrahlung, synchrotron and inverse Compton scattering with the 5.7 eV cm^{-3} stellar photon field that permeates this region (Helfand et al. 2005; strictly speaking, this is the photon density at the galactic center, but given that we need it primarily to provide an upper limit, it will suffice as an estimate of the photon field at the location of G8.7-0.1 as well). The resulting population of these secondary leptons depends on the injection rate (which is tied directly to the rate of pion decay, and subsequently, to the π^0 decay emissivity fixed by the HESS data) and the energy loss rates from the aforementioned emission processes and from Coulomb processes. The cooling time E/\dot{E} for each of these four processes is shown in Figure 5 for an assumed ambient density $n_p = 500 \text{ cm}^{-3}$ and magnetic field strength $B = 10^{-5} \text{ G}$. It is clear that leptons with energy between $\sim 10^2$ and 10^7 MeV will not have time to cool during the remnant's estimated lifetime. The lepton distribution is therefore approximated by using the lower part of the steady-state lepton distribution curve and the secondary lepton injection rate curve multiplied by the age of the remnant.

The broadband spectrum (from radio to TeV energies) for the case of Bohm diffusion is shown in Figure 6. This now includes the various contributions from the secondary leptons as well as photons emitted during pion decays. Clearly, the radiative flux produced by secondary particles falls well below all broadband limits. It is worth noting, however, that a secondary lepton population created by the proton distribution with spectral index of ~ -2.3 (also mirrored by the injected secondaries) can reproduce the observed radio emission if the magnetic field strength is $\sim 0.3 \text{ mG}$. Such field strengths have been associated with SNR - molecular cloud interactions (Claussen et al. 1997; Koralesky et al. 1998; Brogan et al. 2000). However, this choice of spectral index for the protons is clearly at odds with the EGRET observations.

3. Conclusion

We are left with a rather intriguing situation. On the one hand, we have shown that the TeV emission associated with the new source HESS J1804-216 may be a signature of particle acceleration and injection into the ambient medium by the shell of SNR G8.7-0.1, but not by the pulsar PSR J1803-2137 embedded within it. Reasonable values of the physical variables are sufficient to account for its radiative characteristics, and associated flux limits observed from this region at other wavelengths.

On the other hand, the maximum energy of cosmic rays energized by the presumed shock in G8.7-0.1 is severely limited by the acceleration efficiency and time, and would seem to be restricted to values below about 10^5 GeV. This scenario would not support the viability of a CR anisotropy from this region, and would be consistent with the findings of the Auger Observatory, which does not confirm earlier claims based on the SUGAR and AGASA data.

The pulsar model for HESS J1804-216 does not work at TeV energies, but unlike the SNR source, the energy of particles accelerated near the pulsar’s light cylinder reach values as high as ~ 24 EeV. The capability of PSR J1803-2137 to produce such energetic cosmic rays means that a CR anisotropy in the direction of HESS J1804-216 could be accounted for with this model. Such a scenario would require that EeV protons produced nearly 15,000 years ago have not all diffused out of the surrounding, lower density ($< 10 \text{ cm}^{-3}$) region. In contrast, particles associated with the HESS source would result from the SNR-cloud interaction, and populate a denser (and smaller) shell. Such an anisotropy, though, would require the unlikely circumstance of Auger’s findings being incorrect.

To see how these considerations impact the broader context of high-energy activity at the galactic center, let us firstly take it that, as the AUGER data suggest, there really is (currently) no EeV CR anisotropy in this direction. Then we are led to one of the two following conclusions:

1. if the SUGAR and AGASA data and the analyses thereof (suggesting the existence of galactic center CR anisotropies) are broadly correct, then a source both variable on decadal timescales and capable of accelerating particles to beyond 10^{18} eV exists. Only a source associated with a compact object, most likely a pulsar, could satisfy these requirements but, as may be seen above, it is then difficult to conceive of a source that might produce both the required variability and a power-law spectrum of accelerated particles; it would seem, then, that the HESS J1804-216 source and the SUGAR anisotropy cannot be directly attributed to the same object. Likewise, the high-energy galactic center source scenarios described in Crocker et al. (2005a) could not account for the required variability plus power-law spectrum of accelerated

particles.

2. if, on the other hand, the SUGAR and AGASA data and/or the analyses thereof are in error, then the scenarios outlined in Crocker et al. (2005a)—which are predicated on the SUGAR and AGASA anisotropies being real—cannot hold. There also necessarily exists an implicit upper limit on the strength of any 10^{18} eV neutron source located within the field of view of AUGER and, in particular, towards the galactic center. Furthermore, the in-situ high-energy hadronic population inferred on the basis of the TeV radiation detected by the HESS instrument from the galactic center (and also from the J1804-216 source) must cut off below \sim EeV. Alternatively, it may be that, even if this population does continue up to the EeV energy scale as an undistorted power law, the simple scaling behavior for the $pp \rightarrow nX$ type interaction assumed by Crocker et al. (2005a) and also implicitly employed above (given the dearth of direct experimental data on neutron production at these very high center-of-mass energies) fails and, in fact, significantly over-estimates neutron production (Grasso and Maccione 2005).

Should the analysis of the currently available AUGER data be incomplete, so that, in particular, the galactic center (angular) region be CR over-abundant at \sim EeV energies with an amplitude suggested by the AGASA and SUGAR data and consequent analyses, a proton acceleration model with PSR J1803-2137 as the source is a viable explanation for the SUGAR CR anisotropy. We note in this regard that the minimum energy associated with this pulsar’s particle injection is well beyond the HESS data range, so this eventuality would not be impacted by the low energy data. Alternatively, it may be that, as discussed by Crocker et al. (2005a), the SUGAR point source be real but actually located at the galactic center and, therefore, associated not with HESS J1804-216, but rather the galactic center source detected by HESS (this would, of course, require that SUGAR’s directional determination be in error by $\sim 8^\circ$, but then the problem with AGASA’s non-observation of the SUGAR point source would be resolved).

Pulsars such as PSR J1803-2137, embedded within the environment surrounding the SNR G8.7-0.1, can be viable sources of EeV cosmic rays within the Galaxy. This warrants further analysis. In future work, we will examine whether the known population of sources such as this, distributed throughout the Milky Way, can conceivably account for the isotropic component of the CR spectrum observed at \sim EeV energies.

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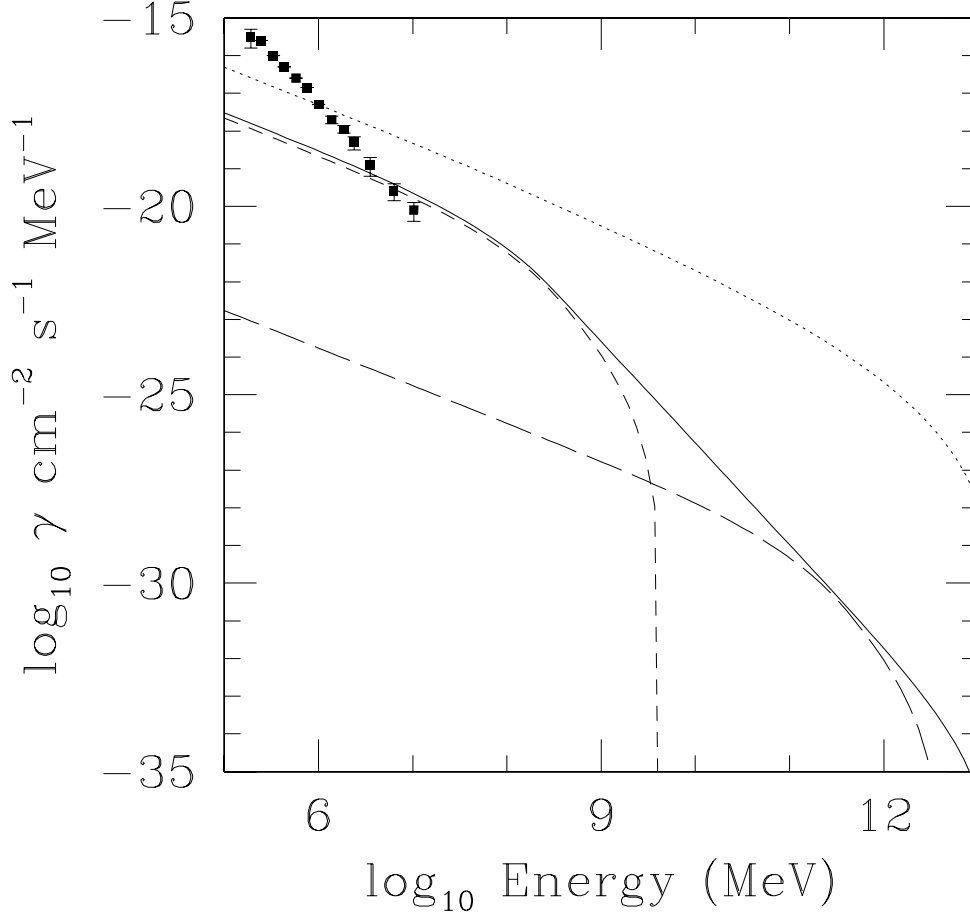


Fig. 1.— Illustrative γ -ray emissivity from the pulsar-powered pion-decay model with $E_{max} \sim 24$ EeV and $E_{min} \sim 6 \times 10^5$ GeV (both calculated from its inferred spin-down age) and an assumed ambient density of 10^3 cm^{-3} . The dotted curve shows the resulting emissivity if the injected particles do not diffuse out of the region. The solid curve shows the resulting emissivity for an idealized distribution that, as a result of diffusion, has a spectral index of -2.7 . In both cases, the π^0 cascade induced by protons with energy E produces a photon spectrum with index ≈ -1 below E_{min} . In the case where diffusion acts to remove high-energy particles from the emission region, the spectrum below E_{min} is almost entirely due to protons with energy $\sim E_{min}$ (whose contributions are shown by the short-dashed curve). Similarly, the long-dashed curve shows the photon spectrum resulting from the π^0 cascade initiated by protons at $E \approx 6 \times 10^8$ GeV. Regardless of how much the energy-dependent diffusion modifies the injected cosmic ray spectrum above E_{min} , the pulsar model therefore cannot account for the steep spectrum (index -2.7) measured by HESS.

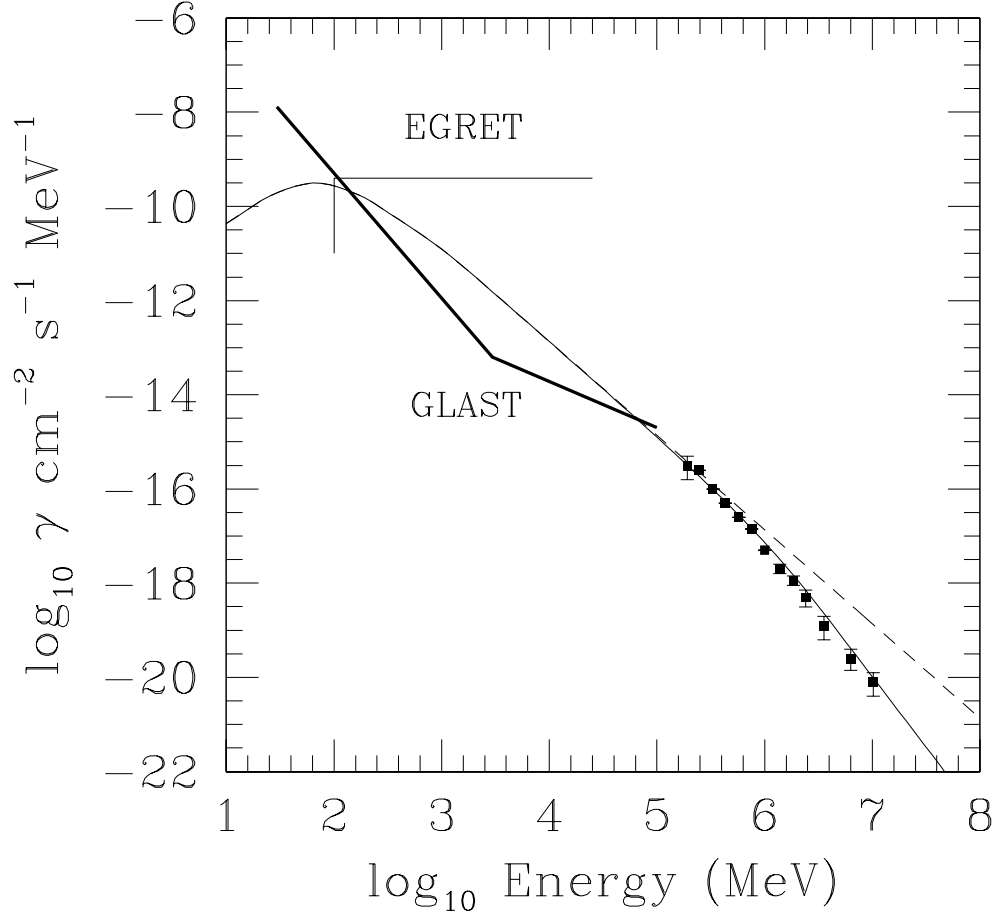


Fig. 2.— The γ -ray emissivity (solid line) for a particle distribution injected with index -2.0 and modified by Bohm diffusion (and $E_{roll} = 7 \times 10^3$ GeV), and the corresponding spectrum (dashed curve) produced without diffusion. The EGRET bar is an upper limit, and the GLAST curve is the simulated one-year all sky survey limit.

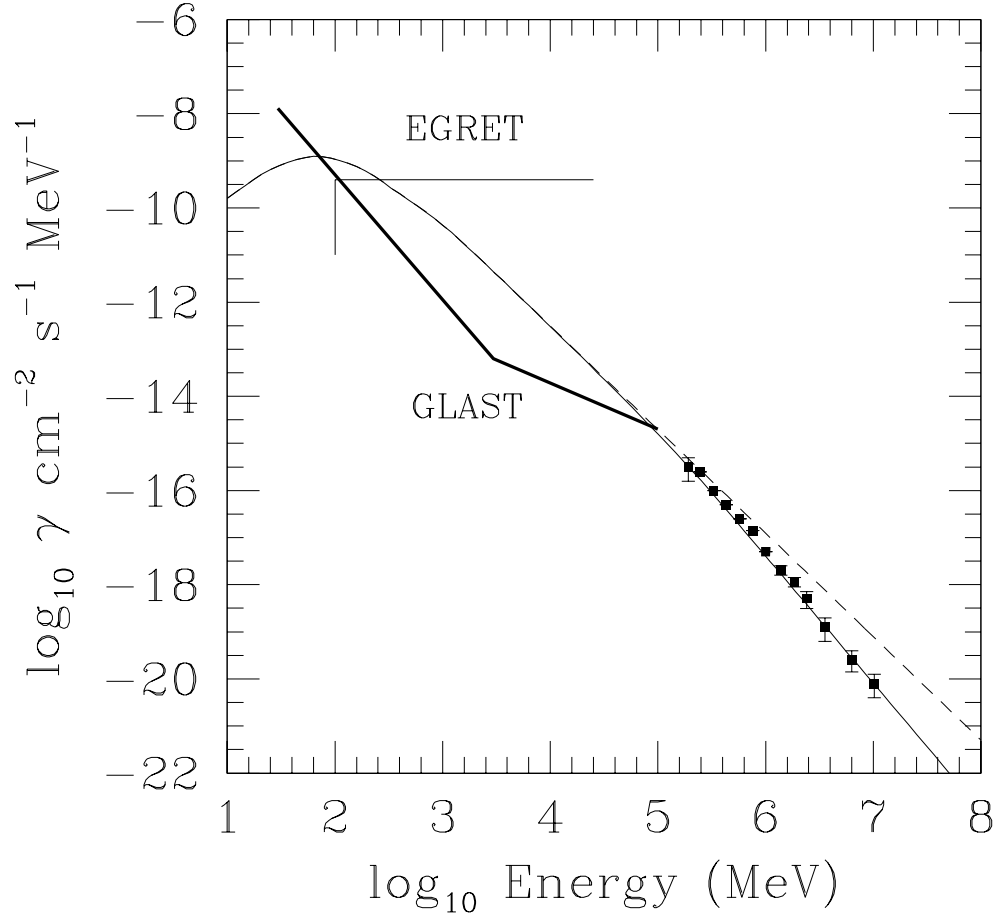


Fig. 3.— Same as Figure 2, except now for Kraichnan diffusion with $E_{roll} = 10^3$ GeV, and an injected particle distribution index -2.2 .

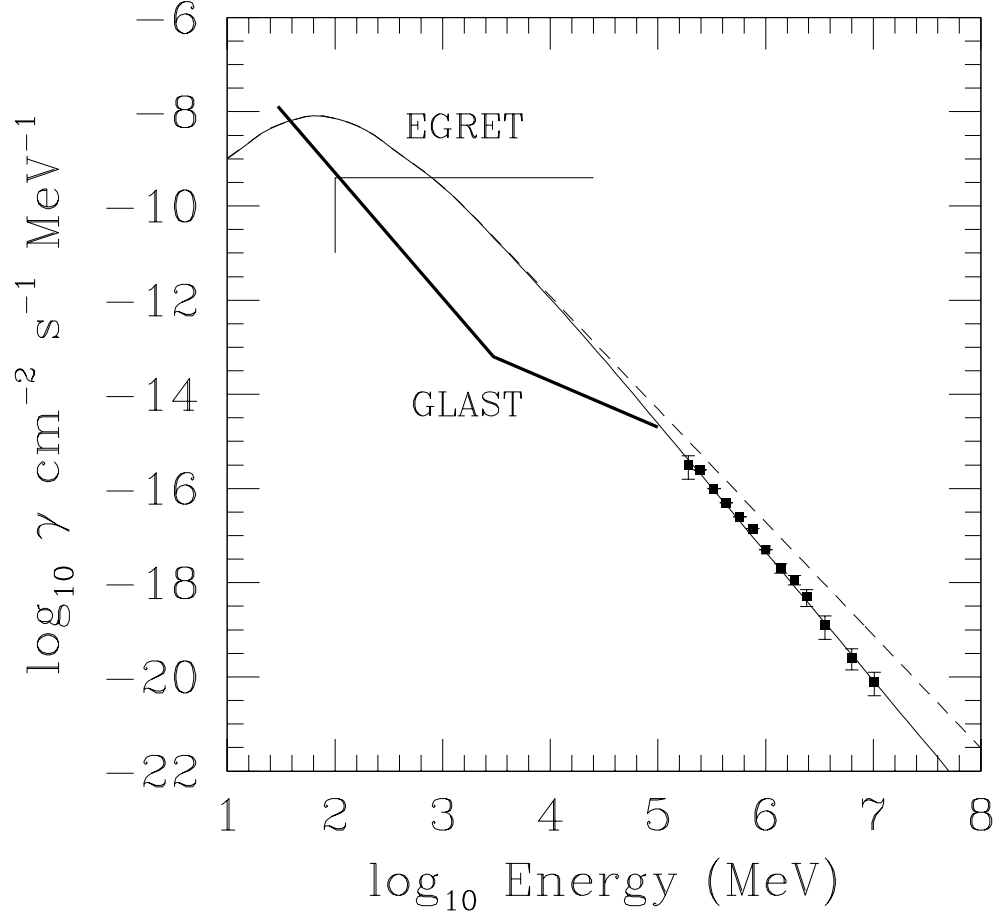


Fig. 4.— Same as Figures 2 and 3, except now for Kolmogorov diffusion with $E_{roll} = 100$ GeV, and an injected particle distribution index -2.4 .

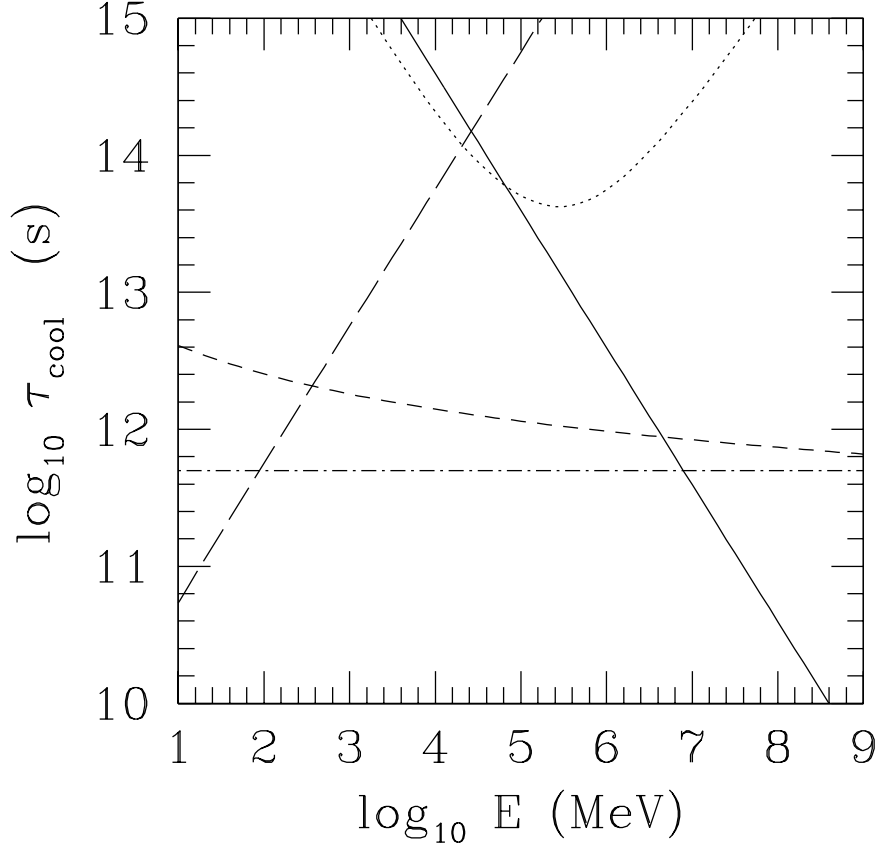


Fig. 5.— The cooling time $\tau = E/\dot{E}$ as a function of energy for leptons interacting with a medium of density $n_H = 500 \text{ cm}^{-3}$ and magnetic field strength $B = 10^{-5} \text{ G}$. Short dashed curve: bremsstrahlung cooling; solid curve: synchrotron cooling; long dashed curve: Coulomb losses; dotted curve: inverse Compton scattering with the ambient stellar photon field.

The dot-dashed curve represents the value of the SNR age.

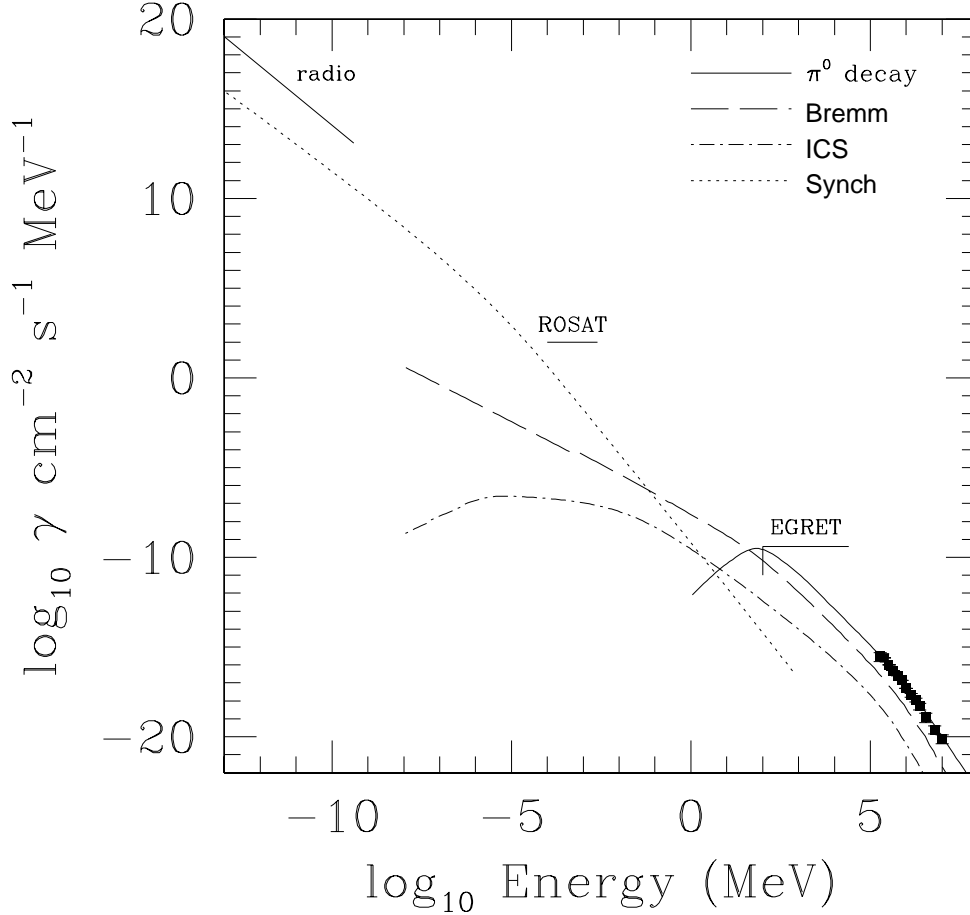


Fig. 6.— The γ -ray emissivity from the SNR-powered pion-decay model with $n_H = 500 \text{ cm}^{-3}$, and $B = 10^{-5} \text{ G}$. The remnant’s age is assumed to be 15,000 years in order to determine the secondary leptons’ (non steady-state) distribution. Solid line: photons produced via the decay of neutral pions; long dashed curve: bremsstrahlung emission from the secondary leptons; dot-dashed line: inverse Compton scattering emission from the secondary leptons interacting with the background stellar field; dotted line: synchrotron emission from the secondary leptons. The HESS data are represented as dark squares. Also shown are the EGRET upper limit, and the measurements made with ROSAT and the VLA, both of which must be considered as upper limits as well, given the differences in field-of-view.